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THE UNIVERSITY OF ALABAMA IN HUNTSVILLE  
HUNTSVILLE, ALABAMA**

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Final Report of Work for  
NAS8-36718

Introduction:

Various individuals from the University of Alabama in Huntsville (UAH) were involved in research related to the work carried out at the Earth Science Division of Marshall Space Flight Center.

In support of the mission to better understand the dynamics of the global atmosphere, John R. Christy and Nathaniel D. Reynolds investigated a wide range of topics. Dr. Christy worked closely with NASA scientist Roy Spencer to develop a data set of precision temperature measurements using the NASA built Microwave Sounding Unit. The data from this effort has received international recognition as they provide a source of precise information for the most difficult of environmental issues in the global climate change arena. In addition, Christy coordinated modeling research with NASA scientist Franklin Robertson with research focussing on the validation of global model output using various satellite data with sophisticated statistical techniques. Reynolds worked with NASA scientist Timothy Miller on idealized flows in a rotating annulus and the application of the results to the general circulation of the atmosphere. Additional work was carried out in investigation of stratospheric ozone fluctuations due to dynamical causes.

In the final analysis, the publication of research results in the refereed literature is the best means to judge the success of the contract. Below are the publications listed by participant.

**John R. Christy**

Publications from research supported by the contract

Refereed Publications:

Karl, T.R., R.W. Knight and J.R. Christy, 1994: Global and hemispheric temperature trends: Uncertainties related to inadequate spatial sampling. *J. Climate* (in press).

Christy, J.R. and S.J. Drouilhet, 1994: Variability in daily, zonal mean lower-stratospheric temperatures. *J. Climate*, 7, 106-120.

Spencer, R.W. and J.R. Christy, 1993: Precision lower stratospheric temperature monitoring with the MSU: Validation and results 1979-91. *J. Climate*, 6, 1194-1204.

Dutton, E. G. and J.R. Christy, 1992: Solar radiative forcing at selected locations and evidence for global lower tropospheric cooling following the eruptions of El Chichon and Pinatubo. *Geophys. Res. Lett.* 19, 2313-2316.

Trenberth, K. E., J. R. Christy and J. W. Hurrell, 1992: Monitoring global monthly mean surface temperatures. *J. Climate*, 5, 1405-1423.

Spencer, R. W. and J. R. Christy, 1992: Precision and radiosonde validation of satellite gridpoint temperature anomalies, Part I: MSU channel 2. *J. Climate*, 5, 847-857.

Spencer, R. W. and J. R. Christy, 1992: Precision and radiosonde validation of satellite gridpoint temperature anomalies, Part II: A tropospheric retrieval and trends during 1979-90. *J. Climate*, 5, 858-866.

Christy, J. R., 1991: Diabatic heating rate estimates from European Centre for Medium-Range Weather Forecasts analyses. *J. Geophys. Res.*, **96**, 5123-5135.

Spencer, R.W. and J.R. Christy, 1991: Response. *Science*, **251**, 317.

Spencer, R. W. , J. R. Christy and N. C. Grody, 1991: Precision tropospheric temperature monitoring 1979-1990. *Palaeogeogr. Palaeoclimatol. Palaeoecol. (Global Planet. Change Sect.)*. **90**, 113-110.

Spencer, R. W. and J. R. Christy, 1990: Precise monitoring of global temperature trends from satellites. *Science*, **247**, 1558-1562.

Spencer, R. W. , J. R. Christy and N. C. Grody, 1990: Global atmospheric temperature monitoring with satellite microwave measurements: Method and results 1979-1985. *J. Climate*, **3**, 1111-1128.

Christy, J. R., K. E. Trenberth and J. R. Anderson, 1989: Large-scale redistributions of atmospheric mass. *J. Climate*, **2**, 137-145.

#### Contributions to Books:

Christy, J. R., "Monitoring Global Temperature Changes from Satellites" *Global Climate Change: Implications, Challenges and Mitigation Measures*, S.K. Majumdar, L.S. Kalkstein, B. Yarnel, E.W. Miller and L.M. Rosenfeld Eds. Pennsylvania Academy of Science, 1992, 566 pp.

#### Published Conference Presentations:

Christy, J.R., 1993: Precision global temperatures from satellites. *Proc. International Conf. on Sustainable Development*. 25-29 January, 1993. New Delhi, India.

Reddy, R.S. and J. R. Christy, 1993: On the relationship between Indian rainfall and tropospheric and stratospheric temperatures. *Proc. International Conf. on Sustainable Development*. 25-29 January, 1993. New Delhi, India.

Christy, J.R. and J.D. Goodridge, 1993: Homogeneous time series from sequentially launched polar orbiters, MSU channels. *Proc. Eighth Conf. Applied Climatology*. 17-22 January, 1993. Anaheim, CA.

Robertson, F.R., E. Barron, S.J. Goodman, D. Fitzjarrald, E. Bishop, J.R. Christy, S. Thompson, D. Pollard, 1993: Genesis climate model: Intercomparison with multiple climate data bases. *Proc. Fourth AMS Symposium on Global Change Studies*, 17-22 January, 1993. Anaheim, CA.

Christy, J.R., 1992: Impacts on global temperatures due to Mt. Pinatubo and the 91-92 ENSO. *Proc. 17th Climate Diagnostics Workshop*. 19-23 October 1992, Norman OK.

Christy, J. R., R.T. McNider and F.R. Robertson, 1991: A comparison of CCM1 and MSU temperatures for 1979-1986. *Proc. Fifth Symposium on Climate Variations*. 14-18 October 1991. Denver CO.

Christy, J. R., and K.E. Trenberth, 1991: Monitoring global monthly surface temperatures. *Proc. Fifth Symposium on Climate Variations*. 14-18 October 1991. Denver CO.

- Christy, J.R., and R.W. Spencer, 1990: Global temperatures from Microwave Sounding Units. *Proc. Fifteenth Climate Diagnostics Workshop*. 29 Oct.-2 Nov. 1990. Asheville NC.
- Christy, J.R., and F.R. Robertson, 1990: The CCM1 at MSFC: Validation against satellite layer temperatures and ECMWF analyses. Workshop on the NCAR Community Climate Model. 16-20 July 1990, Boulder CO.
- Christy, J.R., and R.W. Spencer, 1990: Global tropospheric temperature variations since 1979 as measured from the Microwave Sounding Unit. *Proc. Climate Variations*, 4-7 February, 1990, Anaheim CA.
- Spencer, R.W., and J.R. Christy, 1990: Global tropospheric temperature monitoring with passive microwave radiometers. *Proc. Climate Variations*, 4-7 February, 1990, Anaheim CA.
- Christy, J.R., and R.W. Spencer, 1989: Global tropospheric temperature variations since 1979 as measured from the Microwave Sounding Unit. *Proc. Fourteenth Ann. Climate Diagnostics Workshop*, 16-20 October, 1989, Scripps Institute of Oceanography, La Jolla CA.
- Spencer, R.W., and J.R. Christy, 1989: Global tropospheric temperature monitoring with passive microwave radiometers. *Proc. Fourteenth Ann. Climate Diagnostics Workshop*, 16-20 October, 1989, Scripps Institute of Oceanography, La Jolla CA.
- Robertson, F.R., and J.R. Christy, 1989: Global analyses of water vapor, cloud and precipitation constrained by SSM/I retrievals. IAMAP 89: Fifth Scientific Assembly of the International Association of Meteorology and Atmospheric Physics. 31 July - 12 August, 1989, University of Reading, UK.
- Robertson, F.R., R.W. Spencer and J.R. Christy, 1989: Geophysical parameters from microwave retrievals. Workshop on the use of Satellite Data in the European Centre for Medium Range Weather Forecasts model. 8-12 May 1989, Reading UK.
- Christy, J.R., 1989: Global distribution of diabatic heating rate estimates. *Symposium on the Role of Clouds in Atmospheric Chemistry and Global Climate*. 29 January - 2 February, 1989, Anaheim CA.
- Christy, J.R., 1988: Global scale diabatic heating distributions and atmospheric mass anomalies. *Proc. Thirteenth Ann. Climate Diagnostics Workshop*, 31 October - 3 November 1988, Boston MA.

## **Nathaniel D. Reynolds**

### **Refereed Publications:**

- Fichtl, G.H., N.D. Reynolds, A.E. Johnston, S.I. Adelfang, W. Batts, L. Lott, P.J. Meyer, O.E. Smith, M.S. Swint, and O.H. Vaughn, 1988: Analysis of in-flight winds for shuttle missions STS 51-L. *J. Appl. Met.*, 27, 1232-1241.

### **Published Conference Presentations:**

- Reynolds, N.D., 1989: Storm tracks in an idealized baroclinic flow with topography. *Seventh Conf. on Atmospheric and Oceanic Waves and Stability*. San Francisco, CA, April 1989.

Reynolds, N.D., 1988: Baroclinic wave-mean flow interaction due to the presence of large-scale topography. *Palmen Memorial Symposium on Extratropical cyclones*, Helsinki, Finland, August 1988.

**Research Report**  
**October 1, 1991 - September 30, 1992**

**FNAS Fluid Dynamics Study**  
**NAS8-36718**

**Personnel:** Mr. Gregory N. Cox

**Objective:** Support of the Aspen Global Change Institute and the Ground Truth Studies Program.

**Activities:**

During the period of performance noted above, Mr. Cox assisted in the organization of the 1992 Aspen Global Change Institute's (AGCI) science sessions held during July - August, 1992 in Aspen, Colorado. The sessions provided a forum for an in-depth exploration of current issues on the science of global change. During the reporting period, UAH and the Aspen Global Change Institute also continued to plan and organize activities involved in conducting six weeks of global change cross-disciplinary science sessions for 1992 and 1993.

White paper reports on the 1991 summer AGCI science sessions written by program participants were received during the period of performance. As part of these forums, respected scientists from the general disciplines were brought into a forum to develop and critique ground-truth data bases for utilization of satellite data. New approaches were investigated to improve and expand data bases for ground-truth data to evaluate sensor retrieval.

UAH personnel assisted in the design and implementation of an activity based upon the NASA "Mission to Planet Earth" program. This activity was used by organizers of the 1992 Science Olympiad National Competition held in May, 1992 in Auburn, Alabama.

UAH personnel continued to assist in the coordination the development, training and distribution efforts of the AGCI Ground Truth Studies Program. An evaluation of teacher usage of the GTS program was conducted jointly by UAH and AGCI personnel. Of the seventeen original GTS pilot teachers, the program earned high marks: 68% of the activities earned an overall rating of excellent, 25% good, and only 7% either fair or poor. Based on this information the GTS Teacher Handbook was revised, expanded and reprinted in June 1992.

A telephone survey of 92 out of 449 teachers who had received the Ground Truth Studies Teacher Handbook and varying amounts of training were interviewed to estimate the level of use of GTS and the effect of different training regimens. Reported use of GTS varied with the type and amount of training that the teachers had received. Over 40% of a group of teachers who received 7-hours of instruction as part of the SOPE workshop, reported that they had or planned to use GTS in the 1992/93 school year. Fifty percent of teachers who purchased the GTS Teacher Handbook, but received no training, reported that they had or planned to use GTS in the 1992/93 school year.

Teachers were unanimous in their enthusiasm about the value of Ground Truth Studies to themselves and their classes: 69% gave an overall rating of excellent, and 31% rated it as good, with no marks for either category of fair or poor.

# Precise Monitoring of Global Temperature Trends from Satellites

ROY W. SPENCER AND JOHN R. CHRISTY

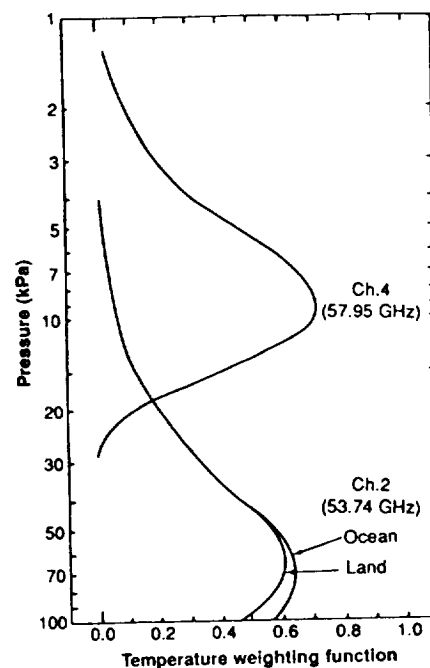
Passive microwave radiometry from satellites provides more precise atmospheric temperature information than that obtained from the relatively sparse distribution of thermometers over the earth's surface. Accurate global atmospheric temperature estimates are needed for detection of possible greenhouse warming, evaluation of computer models of climate change, and for understanding important factors in the climate system. Analysis of the first 10 years (1979 to 1988) of satellite measurements of lower atmospheric temperature changes reveals a monthly precision of  $0.01^{\circ}\text{C}$ , large temperature variability on time scales from weeks to several years, but no obvious trend for the 10-year period. The warmest years, in descending order, were 1987, 1988, 1983, and 1980. The years 1984, 1985, and 1986 were the coolest.

ACCURATE ESTIMATES OF GLOBAL ATMOSPHERIC TEMPERATURES are needed for evaluation of global climate models, detection of climate changes, and a better understanding of the climate system. Global temperatures have generally been estimated from surface temperature records, but there has been much debate regarding, for example, whether these data provide evidence of recent greenhouse warming (1). The primary source of uncertainty is the relatively sparse distribution of thermometers over the surface of the earth. Most of the earth is covered by oceans, and vast oceanic areas go unmeasured. Even over land, the coverage is greatest where the population is greatest; therefore, remote land areas also go unmeasured. An additional problem is that urban sites, which represent only a small part of the globe but where many long-term measurements have been made, have warmed because of heat from man-made structures, and thus these records are difficult to interpret (2, 3). Depending upon how the thermometer data are analyzed, various answers can be expected. In contrast to surface thermometers, sensors on satellite platforms can provide nearly complete earth coverage in as little as one day and can obtain measurements from various levels of the atmosphere. Calibration of satellite sensors is particularly difficult, however. For climate temperature monitoring a precision of  $0.1^{\circ}\text{C}$  is needed, a goal that has been perceived as difficult for any earth viewing radiometer. The difficulty arises from uncertainty about the long-term stability of satellite sensors. In this article, we show that accurate long-term global temperature measurements can be obtained from satellites

now operating and discuss data obtained from 1979 to 1988.

**Methodology.** In late 1978, a series of passive microwave radiometers was launched aboard the TIROS-N series of National Oceanic and Atmospheric Administration (NOAA) satellites. These radiometers, or microwave sounding units (MSUs), are Dicke-type radiometers designed to measure the thermal emission of radiation by atmospheric  $\text{O}_2$  at four frequencies near 60 GHz (4). The atmospheric concentration of  $\text{O}_2$  is constant in both space and time (5), and thus  $\text{O}_2$  provides a stable temperature tracer. The strong interaction of radiation from 50 to 70 GHz with  $\text{O}_2$  through rotational energy transitions causes absorption and emission. As the channel frequency of the MSU approaches the 60-GHz peak in this absorption complex, higher levels in the atmosphere will be measured (Fig. 1) (6). We have analyzed data from MSU channel 2, which measures the temperature of the middle troposphere at 53.74 GHz. At 57.95 GHz, MSU channel 4 can be used to monitor temperatures of the lower stratosphere. MSU channels 1 and 3 are more difficult to interpret for climate purposes because channel 1 is too sensitive to surface effects on the earth and cloud water, whereas channel 3 detects radiation from a strong temperature-transition region between the troposphere and stratosphere (the tropopause). The four channels have traditionally been used to obtain vertical profiles of temperature in remote regions of the earth where weather balloon data are not available. However, because the weighting

**Fig. 1.** Temperature weighting functions (unitless) for MSU channels 2 (mid-troposphere) and 4 (lower stratosphere). Also shown are the different channel 2 weighting functions for ocean and land surfaces, which arise because the less emissive ocean reflects more of the downwelling atmospheric radiation back upward. Sensitivity to the surface radiation itself cannot be implied from the magnitudes at the intersection of the curves with the surface. [Adapted from (6)]



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## Variability in Daily, Zonal Mean Lower-Stratospheric Temperatures

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### ABSTRACT

Satellite data from the microwave sounding unit (MSU) channel 4, when carefully merged, provide daily zonal anomalies of lower-stratosphere temperature with a level of precision between  $0.01^{\circ}$  and  $0.08^{\circ}\text{C}$  per  $2.5^{\circ}$  latitude band. Global averages of these daily zonal anomalies reveal the prominent warming events due to volcanic aerosol in 1982 (El Chichón) and 1991 (Mt. Pinatubo), which are on the order of  $1^{\circ}\text{C}$ .

The quasi-biennial oscillation (QBO) may be extracted from these zonal data by applying a spatial filter between  $15^{\circ}\text{N}$  and  $15^{\circ}\text{S}$  latitude, which resembles the meridional curvature. Previously published relationships between the QBO and the north polar stratospheric temperatures during northern winter are examined but were not found to be reproduced in the MSU4 data.

Sudden stratospheric warmings in the north polar region are represented in the MSU4 data for latitudes poleward of  $70^{\circ}\text{N}$ . In the Southern Hemisphere, there appears to be a moderate relationship between total ozone concentration and MSU4 temperatures, though it has been less apparent in 1991 and 1992.

In terms of empirical modes of variability, the authors find a strong tendency in EOF 1 (39.2% of the variance) for anomalies in the Northern Hemisphere polar regions to be counterbalanced by anomalies equatorward of  $40^{\circ}\text{N}$  and  $40^{\circ}\text{S}$  latitudes. In addition, most of the modes revealed significant power in the 15–20 day period band.

### 1. Introduction

Documenting and understanding the variability of the stratosphere for global change research has been a challenging part of the overall effort to study the earth system. The importance of such studies addresses concerns as to whether a portion of the observed stratospheric variability is due to anthropic impacts on the atmosphere (i.e., ozone depletion) and whether a fundamental and potentially damaging change may be occurring. The purpose of this paper is to provide a data analysis of the daily lower-stratospheric zonal mean temperature fluctuations as have been observed from the microwave sounding units (MSUs). It will therefore provide information on the types of variations that occur and how these variations relate to known fluctuations and further, will establish a base from which to compare future fluctuations and trends in these data. Though this data record begins only recently (1979), it brings global coverage and high precision to the global climate change research arena.

The MSU has been a part of the sensor package aboard the *TIROS-N* family of NOAA polar orbiters

since December 1978. The instrument has provided so-called brightness temperatures ( $T_b$ ) at four frequencies near the 60-GHz oxygen absorption band almost continuously since the first was launched. At intervals of one to two years, new satellites have been placed in orbit to replace older ones. Generally, two orbiters are in operation on any given day, one with a southbound 7:30 a.m. (northbound 7:30 p.m.) local equator crossing time ("morning") and one with a 2:30 p.m./a.m. crossing time ("afternoon").

Spencer and Christy (1993, hereafter SC) have shown that the precision of the deduced physical atmospheric temperature from the microwave  $T_b$  is especially high for Channel 4 (MSU4), the frequency that monitors the  $T_b$  in (approximately) the 100–50-hPa layer or lower stratosphere. The MSU4 weighting function peaks at 75 hPa and has half-power values at 120 and 40 hPa, giving a broad overlap with the 100–50-hPa layer. Independent assessments of gridpoint ( $2.5^{\circ}$ ) accuracy for pentads (5-day means) show a standard error of measurement ( $\sigma_e$ ) for a single satellite to be less than  $0.25^{\circ}\text{C}$  for most of the globe and less than  $0.15^{\circ}\text{C}$  for the tropics. Because two satellites are normally providing data, the actual  $\sigma_e$  of the processed archive is further reduced by a factor of 0.7 most of

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## Precision and Radiosonde Validation of Satellite Gridpoint Temperature Anomalies. Part I: MSU Channel 2

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### ABSTRACT

In Part I of this study, monthly  $2.5^\circ$  gridpoint anomalies in the *TIROS-N* satellite series Microwave Sounding Unit (MSU) channel 2 brightness temperatures during 1979–88 are evaluated with multiple satellites and radiosonde data for their climate temperature monitoring capability. The MSU anomalies are computed about a 10-year mean annual cycle at each grid point, with the MSUs intercalibrated to a common arbitrary level. The intercalibrations remove relative biases between instruments of up to several tenths of a degree celsius. The monthly gridpoint anomaly agreement between concurrently operating satellites reveals single-satellite precision generally better than  $0.07^\circ\text{C}$  in the tropics and better than  $0.15^\circ\text{C}$  at higher latitudes. Monthly anomalies in radiosonde channel 2 brightness temperatures computed with the radiative transfer equation compare very closely to the MSU measured anomalies in all climate zones, with correlations generally from 0.94 to 0.98 and standard errors of  $0.15^\circ\text{C}$  in the tropics to  $0.30^\circ\text{C}$  at high latitudes. Simplification of these radiative transfer calculations to a static weighting profile applied to the radiosonde temperature profile leads to an average degradation of only  $0.02^\circ$  in the monthly skill. In terms of a more traditionally measured quantity, the MSU channel 2 anomalies match best with either the radiosonde 100–20-kPa or 100–15-kPa layer anomalies. No significant spurious trends were found in the 10-yr satellite dataset compared to the radiosondes that would indicate a calibration drift in either system. Thus, sequentially launched, overlapping passive microwave radiometers provide a useful system for monitoring intraseasonal to interannual climate anomalies and offer hope for monitoring of interdecadal trends from space. The Appendix includes previously unpublished details of the MSU gridpoint anomaly dataset construction. Part II of this study addresses the removal from channel 2 of the temperature influence above the 30-kPa level, providing a sharper and thus potentially more useful weighting function for monitoring lower tropospheric temperatures.

### 1. Background

The potential of externally calibrated microwave radiometers for precision monitoring of climate change was demonstrated by Spencer and Christy (1990, hereafter SC) and Spencer et al. (1990, hereafter SCG) in the context of deep-tropospheric and lower-stratospheric brightness temperature ( $T_b$ ) anomalies. With an instrument calibration totally independent of any radiosonde data, intercomparisons between simultaneously operating Microwave Sounding Units (MSUs) on morning and afternoon *TIROS-N* satellites revealed agreement to  $0.01^\circ\text{C}$  for monthly, globally averaged  $T_b$  anomalies and instrument stability to better than  $0.01^\circ\text{C}$  over a 2-year overlap period. While a precision of  $0.01^\circ\text{C}$  might seem implausible in view of the MSU single-sample instrumental noise of  $0.3^\circ\text{C}$ , a month's

worth of global observations involves many ( $10^6$ ) measurements. This would reduce the noise to  $0.0003^\circ\text{C}$  if the measurement errors are randomly distributed, but the different space and time sampling characteristics of the concurrently operating morning and afternoon satellites degrade the precision to  $0.01^\circ\text{C}$ . Whereas the previously published results addressed the precision of the satellite measurements on hemispheric and global scales, we now extend this evaluation to the  $2.5^\circ$  gridpoint scale where individual radiosonde stations can be used as an independent tool for verifying the satellite data quality.

A fundamental question often asked is, What do the channel 2  $T_b$  anomalies represent? First let us address the deep-layer nature of the measurement. The channel 2 weighting function (Fig. 1) is vertically broad and represents the vertical distribution (in  $\log p$  coordinates) of the satellite-measured radiation over a layer extending from the surface to above 30 kPa. The bulk of this microwave radiation is thermally emitted by molecular oxygen with an intensity, via the Planck

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## Precision and Radiosonde Validation of Satellite Gridpoint Temperature Anomalies. Part II: A Tropospheric Retrieval and Trends during 1979–90

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(Manuscript received 9 April 1991, in final form 20 November 1991)

### ABSTRACT

*TIROS-N* satellite Microwave Sounding Unit (MSU) channel 2 data from different view angles across the MSU scan swath are combined to remove the influence of the lower stratosphere and much of the upper troposphere on the measured brightness temperatures. The retrieval provides a sharper averaging kernel than the raw channel 2 weighting function, with a peak lowered from 50 kPa to 70 kPa and with only slightly more surface influence than raw channel 2. Monthly  $2.5^\circ$  gridpoint anomalies of this tropospheric retrieval compared between simultaneously operating satellites indicate close agreement,  $0.15^\circ\text{C}$  in the tropics to around  $0.30^\circ\text{C}$  over much of the higher latitudes. The agreement is not as close as with raw channel 2 anomalies because synoptic-scale temperature gradient information across the 2000-km swath of the MSU is lost in the retrieval procedure and because the retrieval involves the magnification of a small difference between two large numbers. Single gridpoint monthly anomaly correlations between the satellite measurements and the radiosonde calculations range from around 0.95 at high latitudes to below 0.8 in the tropical west Pacific, with standard errors of estimate of  $0.16^\circ\text{C}$  at Guam to around  $0.50^\circ\text{C}$  at high-latitude continental stations. Calculation of radiosonde temperatures with a static weighting function instead of the radiative transfer equation degrades the standard errors by an average of less than  $0.04^\circ\text{C}$ . Of various standard tropospheric layers, the channel 2 retrieval anomalies correlate best with radiosonde 100–50- or 100–40-kPa-thickness anomalies. A comparison between global and hemispheric anomalies computed for raw channel 2 data versus the tropospheric retrieval show a correction in the 1979–90 time series for the volcano-induced stratospheric warming of 1982–83, which was independently observed by MSU channel 4. This correction leads to a slightly greater tropospheric warming trend in the 12-year time series (1979–90) for the tropospheric retrieval [ $0.039^\circ\text{C}$  ( $\pm 0.03^\circ\text{C}$ ) per decade] than for channel 2 alone [ $0.022^\circ\text{C}$  ( $\pm 0.02^\circ\text{C}$ ) per decade].

### 1. Introduction

In Part I of this study we showed the excellent agreement between separate *TIROS-N* satellites when independently measuring monthly anomalies of the Microwave Sounding Unit (MSU) channel 2  $T_b$  at the  $2.5^\circ$  gridpoint level. The average gridpoint agreement between satellites was better than  $0.07^\circ\text{C}$  over the tropical oceans and usually better than  $0.15^\circ\text{C}$  elsewhere. When the satellite measurements were compared to radiosonde measurements of 10 years of monthly anomalies, good agreement was found with many correlations over 0.95 and standard errors of estimate of  $0.15^\circ\text{C}$  in the tropics to  $0.25^\circ\text{C}$  at high latitudes. In terms of conventionally measured atmospheric layers, the channel 2 anomalies correlated best with 100–15-kPa thickness anomalies. Decadal trends

in both the satellite and radiosonde time series, as well as intercomparisons between satellites, showed no evidence for instrumental drift in MSU channel 2.

However, lower-stratospheric temperatures can behave differently than tropospheric temperatures, making the channel 2 overlap into these two regions a disadvantage for monitoring of tropospheric temperatures. Examination of 10-year radiosonde temperature trends for different layers of the atmosphere (Table 1) reveals that different regional trends can be experienced depending on the layer in question, even within the troposphere. Most of these regions, with the exception of the tropical Pacific, experienced considerably different trends above versus below the 30-kPa level. Note also that these 10-year trends are quite variable from region to region, making the lack of radiosonde data in remote regions a significant source of uncertainty in monitoring “global” temperature trends with radiosonde data. These differences suggest the need to remove as much of the upper troposphere and lower stratosphere as possible from the channel 2 measurements if maximum

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# SOLAR RADIATIVE FORCING AT SELECTED LOCATIONS AND EVIDENCE FOR GLOBAL LOWER TROPOSPHERIC COOLING FOLLOWING THE ERUPTIONS OF EL CHICHÓN AND PINATUBO

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**Abstract.** As a result of the eruption of Mt. Pinatubo (June 1991), direct solar radiation was observed to decrease by as much as 25-30% at four remote locations widely distributed in latitude. The average total aerosol optical depth for the first 10 months after the Pinatubo eruption at those sites is 1.7 times greater than that observed following the 1982 eruption of El Chichón. Monthly-mean clear-sky total solar irradiance at Mauna Loa, Hawaii, decreased by as much as 5% and averaged 2.4% and 2.7% in the first 10 months after the El Chichón and Pinatubo eruptions, respectively. By September 1992 the global and northern hemispheric lower tropospheric temperatures had decreased 0.5°C and 0.7°C, respectively compared to pre-Pinatubo levels. The temperature record examined consists of globally uniform observations from satellite microwave sounding units.

## Introduction

The physical mechanisms by which a volcanic eruption can cool the earth have been discussed extensively in the literature [Pollack et al., 1976; Harshvardhan, 1979; Hansen et al., 1992; and others]. Atmospheric temperature records have been examined for volcanic effects by Mitchell [1971], Mass and Schneider [1977], Mass and Portman [1989], and others. The inferred global coolings following major eruptions have generally been less than 0.5°C. Sulfur dioxide emitted from the volcano and injected into the stratosphere leads to the formation of small, < 1.0 µm droplets of sulfuric acid that persist for up to several years. These droplets, which spread over large portions of the globe, are primarily responsible for scattering some incoming solar radiation back to space but fail to absorb sufficient outgoing thermal radiation to offset solar losses at the surface and, hence, result in a potential for global near-surface cooling. The particular timing, location, and eventual stratospheric aerosol loading can all affect the potential climatic impact of individual eruptions. Although some possible consequences of volcanic eruptions are known, there is complete uncertainty as to when a volcanic eruption will occur, how significant a particular eruption will be, and exactly how the volcanic effects will be interwoven with other climatic variations.

Stratospheric aerosol optical depth has been identified as the volcanic by-product that has the greatest single influence on radiation budget perturbations [Lacis et al., 1992], which in turn perturb the climate. This paper examines time series of aerosol optical depth obtained at four globally distributed remote sites, total solar irradiance observed at Mauna Loa, Hawaii, and the global temperature data that is obtained from microwave sounding units (MSUs) aboard operational NOAA satellites as processed and reported by Spencer and Christy [1990]. All the data sets began before 1980 and are at least

seasonally continuous to date, and hence contain information on the effects of the eruptions of El Chichón in Mexico (April 1982) and Pinatubo in the Philippines (June 1991).

## Observations of Optical Depth, Irradiance, and Temperature

Aerosol optical depth is the aerosol contribution to the exponent in the exponential decrease in a beam of electromagnetic radiation as it passes through the atmosphere and can be determined for solar radiation from spectral measurements of the direct solar beam by identifying and eliminating optical depth contributions from other atmospheric constituents [e.g. Shaw, 1983; Dutton et al., 1983;]. In 1976, the NOAA Climate Monitoring and Diagnostics Laboratory (CMDL) [then NOAA Geophysical Monitoring for Climatic Change, (GMCC) program] established a direct solar beam monitoring project utilizing pyrheliometers and wideband Schott glass cutoff filters. Observations have been made routinely at four sites since 1977: Barrow, Alaska (BRW) at 71° N; Mauna Loa, Hawaii (MLO) at 19° N; American Samoa (SMO) at 14° S; and the South Pole (SPO) at 90° S. These sites were specifically chosen to be globally distributed by latitude and distant from significant particulate and gaseous sources that would interfere with global baseline measurements.

For the CMDL monitoring project, aerosol optical depth is derived from the spectral pyrheliometer data set by matching observations to solar irradiance calculations using a relatively simple radiative transfer (RT) model. The spectral one-layer RT model of Bird and Riordan [1986] has been used consistently for the results reported here. Some additional details of this aerosol optical depth retrieval procedure were given in Bodhaine and Rosson [1988]. This wideband method, although not as accurate or precise as monochromatic techniques, has proven sufficiently stable to provide a valuable aerosol optical depth record from all four CMDL sites from 1977 to date.

Following the eruptions of El Chichón and Pinatubo, decreases of 25 to 30% in direct solar irradiance were recorded by the CMDL pyrheliometers. Data for the entire period of record for all sites were reduced to obtain mean aerosol optical depth (a unitless quantity) for the wavelength range from 0.53 to 0.69 µm. The results shown in Figure 1 are for monthly average anomalies relative to a base of the non-volcanic years with mean seasonal variations removed. The measurement accuracy for the computed optical depth is ±0.04 with the overall precision <±0.02 based on limited comparisons with sunphotometer derived optical depths. Figure 1 shows that El Chichón and Pinatubo were both detected at all four locations. El Chichón had a larger impact in the northern hemisphere than in the southern hemisphere; optical depth anomalies at both MLO and BRW reached mean values of ≥0.20, but Samoa and South Pole only reached about 0.06. All four sites indicate a 3- to 4-year decay to values indistinguishable from background. The maximum optical depth following the Pinatubo eruption at all sites except MLO is greater than that following El Chichón.

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## Monitoring Global Monthly Mean Surface Temperatures

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### ABSTRACT

An assessment is made of how well the monthly mean surface temperatures for the decade of the 1980s are known. The sources of noise in the data, the numbers of observations, and the spatial coverage are appraised for comparison with the climate signal, and different analyzed results are compared to see how reproducible they are. The data are further evaluated by comparing anomalies of near-global monthly mean surface temperatures with those of global satellite channel 2 microwave sounding unit (MSU) temperatures for 144 months from 1979 to 1990. Very distinctive patterns are seen in the correlation coefficients, which range from high ( $>0.8$ ) over the extratropical continents of the Northern Hemisphere, to moderate ( $\sim 0.5$ ) over tropical and subtropical land areas, to very low over the southern oceans and tropical western Pacific. The physical difference between the two temperature measurements is one factor in these patterns. The correlation coefficient is a measure of the signal-to-noise ratio, and largest values are found where the climate signal is largest, but the spatial variation in the inherent noise in the surface observations over the oceans is the other major factor in accounting for the pattern.

Over the oceans, sea surface temperatures (SSTs) are used in the surface dataset in place of surface air temperature and the Comprehensive Ocean-Atmosphere Data Set (COADS) has been used to show that 80% of the monthly mean air temperature variance is accounted for in regions of good data coverage. A detailed analysis of the sources of errors in in situ SSTs and an overall estimate of the noise are obtained from the COADS by assessing the variability within  $2^\circ$  longitude by  $2^\circ$  latitude boxes within each month for 1979. In regions of small spatial gradient of mean SST, individual SST measurements are representative of the monthly mean in a  $2^\circ$  box to within a standard error of  $1.0^\circ\text{C}$  in the tropics and  $1.2^\circ$  to  $1.4^\circ\text{C}$  in the extratropics. The standard error is larger in the North Pacific than in the North Atlantic and much larger in regions of strong SST gradient, such as within the vicinity of the Gulf Stream, because both within-month temporal variability and within- $2^\circ$  box spatial variability are enhanced. The total standard error of the monthly mean in each box is reduced approximately by the square root of the number of observations available. The overall noise in SSTs ranges from less than  $0.1^\circ\text{C}$  over the North Atlantic to over  $0.5^\circ\text{C}$  over the oceans south of about  $35^\circ\text{S}$ . Greater daily variability in surface marine air temperatures than in SSTs means that two to three times as many observations are needed per month to reduce the noise in the monthly mean air temperature to the same level as for SST. Tests of the reproducibility of SSTs in analyses from the U.K. Meteorological Office (UKMO) and the U.S. Climate Analysis Center (CAC) and from COADS reveal monthly anomaly correlations on a  $5^\circ$  grid exceeding 0.9 over the northern oceans but less than 0.6 in the central tropical Pacific and south of about  $35^\circ\text{S}$ . Root-mean-square differences between CAC and UKMO monthly SST anomalies exceed  $0.6^\circ\text{C}$  in the regions where the correlation is lower than about 0.6.

With the marked exception of the eastern tropical Pacific, where the large El Niño signal is easily detected, there are insufficient numbers of SST observations to reliably define SST or surface air temperature monthly mean anomalies over most of the oceans south of about  $10^\circ\text{N}$ . The use of seasons rather than months can improve the signal-to-noise ratio if careful treatment of the annual cycle is included. For seasonal means, SST anomalies cannot be reliably defined south of  $20^\circ\text{S}$  in the eastern Pacific and south of  $\sim 35^\circ\text{S}$  elsewhere except near New Zealand. In light of the noise estimates and the much fewer numbers of observations in the past, difficulties in establishing temperatures from the historical record are discussed.

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# Diabatic Heating Rate Estimates From European Centre for Medium-Range Weather Forecasts Analyses

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Vertically integrated diabatic heating rate estimates ( $H$ ) calculated from 32 months of European Centre for Medium-Range Weather Forecasts daily analyses (May 1985–December 1987) are determined as residuals of the thermodynamic equation in pressure coordinates. Values for global, hemispheric, zonal, and grid point  $H$  are given as they vary over the time period examined. The distribution of  $H$  is compared with previous results and with outgoing longwave radiation (OLR) measurements. The most significant negative correlations between  $H$  and OLR occur for (1) tropical and northern hemisphere mid-latitude oceanic areas and for (2) zonal and hemispheric mean values for periods less than 90 days. Largest positive correlations are seen in periods greater than 90 days for the northern hemispheric mean and continental areas of North Africa, North America, northern Asia, and Antarctica. The physical basis for these relationships is discussed. An interyear comparison between 1986 and 1987 reveals the El Niño–Southern Oscillation signal.

## 1. INTRODUCTION

The sources of diabatic heating in the atmosphere arise from the release of latent heat during condensation/deposition, the transfer of heat from the Earth's surface, absorption of solar and infrared radiation, and frictional dissipation. The dry atmosphere responds to this diabatic forcing by changes in state variables (temperature, density) and by the creation of mass circulations. One may infer the magnitude of the diabatic forcing by carefully measuring the atmospheric response. This approach to calculating the diabatic heating rate is known as the indirect method, since it determines the rate as a residual of the thermodynamic equation [Kasahara and Mizzi, 1985].

Atmospheric diabatic heating is not constant in time or space, having large-scale variability which has consequences for the global weather. Previous studies have demonstrated how anomalous forcing over one region has significant impact on the circulation regimes elsewhere [Hoskins and Karoly, 1981; Geisler *et al.*, 1985; Held and Kang, 1987]. Recently, Trenberth *et al.* [1988] suggested that the hot dry spring of 1988 over the central and eastern United States was related to global circulation adjustments as a response to anomalous atmospheric heating by warm ocean temperatures in the central Pacific. From an operational point of view, Kasahara *et al.* [1987] indicate the value of initializing model runs with accurate diabatic heating in the tropics. W. A. Heckley (personal communication, 1989) has demonstrated that global forecasts, when initialized with precipitation rates (diabatic heating) from infrared satellite retrievals, are improved over standard initialization schemes. These and many other research efforts provide impetus for the quantification of atmospheric heating rates and the associated response of the circulation.

However, as was demonstrated by Boer [1986], Holopainen and Fortelius [1986], and Savijärvi [1988], the global distribution of diabatic heating, in a time-mean sense, is not well known, since various results differ in many respects. Not only is the magnitude of the forcing in question but in

many regions the sign (heating or cooling) is not known for the annual time-mean. Because diabatic effects force the global atmosphere and its associated general circulation, it is extremely important that the spatial and temporal variability of this forcing be known.

Since diabatic forcing is not directly measurable, verification of any calculation is difficult. However, we do know that latent heating due to convective systems is a primary component of diabatic heating in low latitudes [Morrissey, 1986]. As such, it is possible to use observations of outgoing longwave radiation (OLR) as a proxy for these large precipitating systems [Kasahara *et al.*, 1987]. One would expect a negative correlation between the diabatic heating rate of such a precipitating system and OLR to result. On interseasonal time scales however, a different process would be observed over the extratropical land areas, because the cold winter continents are regions of cooling and are also viewed much colder than adjacent oceanic areas in the OLR. The reverse would be observed in summer, so that one would expect a positive correlation between OLR and heating rates over continents in the higher latitudes.

The goals of the present research are (1) to present calculations (or estimates) of the vertically integrated global distribution of diabatic heating rates from global operational analyses, (2) to examine their variability in space and time, and (3) to compare the results with OLR data on a variety of time scales. In so doing, a clearer picture of the fundamental forcing that drives the general circulation will be provided. The data and method for the task at hand are described in the section below. In section 3, results of the diabatic calculations are given, and in section 4 the heating rates and OLR are compared. A discussion and summary section concludes the work.

## 2. DATA AND METHOD

### Diabatic Heating Rate

The global atmospheric data examined here are the twice daily (0000 and 1200 UT) analyses produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). Available to us are horizontal winds ( $u$ ,  $v$ ),

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